LP2EA
Laboratoire de Physique, Énergie, Environnement et ses Applications

Scalars 2025

MARRAKECH
جامعة القاضي عياض
UNIVERSITÉ CADI AYYAD

Vector-like T Bounds at the LHC: Impact of 2HDM-II

Ech-chaouy Mohamed

In collaboration with:
R. Benbrik, M. Boukidi, M. Berrouj, S. Moretti, K. Salime

arXiv:2512.xxxxx

Motivation

- Vector-like quarks (VLQs) are hypothetical particles whose left- and right-handed components transform identically under the SU(2) symmetry.
- VLQs arise in several models, including composite Higgs theories, Little Higgs models, and Two-Higgs-Doublet Models (2HDMs).

$$
\begin{aligned}
& T^0_{L,R}\,, \quad B^0_{L,R} && \text{(singlets)}\,,\\
& (X\,T^0)_{L,R}\,, \quad (T^0\,B^0)_{L,R}\,, \quad (B^0\,Y)_{L,R} && \text{(doublets)}\,,\\
& (X\,T^0\,B^0)_{L,R}\,, \quad (T^0\,B^0\,Y)_{L,R} && \text{(triplets)}\,.
\end{aligned}
$$

- They have not been detected at the LHC. Current searches exclude VLQ masses up to $m_{\text{VLQ}} \simeq 1.7$ TeV.
- 2HDMs extended by VLQs predict new beyond-the-Standard-Model (BSM) decay channels, which can dominate over the Standard Model channels.

2HDM Potential

2HDM potential under $\mathbb{Z}_2$ symmetry:

$$V_{2HDM}^{Z_2} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}], \quad (1)$$

Higgs doublets in 2HDM framework:

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}. \quad (2)$$

- $\Rightarrow$ Two CP-even Higgs bosons: H, h, $H^{SM} = h\sin(\alpha-\beta) - H\cos(\alpha-\beta)$
- $\Rightarrow$ One CP-odd Higgs boson: A
- $\Rightarrow$ A pair of charged Higgs bosons: $H^\pm$

2HDM-II + Vector-Like T Quark (VLT)

The general renormalizable Yukawa Lagrangian, describing fermion interactions and mass terms, is:

$$-\mathcal{L} \supset y^u\, \bar{Q}_L^0 \tilde{H}_2 u_R^0 + y^d\, \bar{Q}_L^0 H_1 d_R^0 + M_u^0 \bar{u}_L^0 u_R^0 + M_d^0 \bar{d}_L^0 d_R^0 + \text{h.c.} \qquad (3)$$

The relationship between the charge 2/3 weak and mass eigenstates can be expressed as follows:

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = U^u_{L,R} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^u_{L,R} & -\sin\theta^u_{L,R} e^{i\phi_u} \\ \sin\theta^u_{L,R} e^{-i\phi_u} & \cos\theta^u_{L,R} \end{pmatrix} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix}. \qquad (4)$$

From diagonalization of the mass matrix, we get:

$$\begin{aligned} \tan\theta_R^q &= \frac{m_q}{m_Q} \tan\theta_L^q \quad (\text{singlets, triplets}), \\ \tan\theta_L^q &= \frac{m_q}{m_Q} \tan\theta_R^q \quad (\text{doublets}), \end{aligned} \qquad (5)$$

LHC VLT Bounds

Considering only the SM+VLQ, the T quark decays via three channels:

$$T \to Wb, \quad T \to Zt, \quad \text{and} \quad T \to ht.$$

These satisfy:

$$\mathcal{BR}(T \to Wb) + \mathcal{BR}(T \to Zt) + \mathcal{BR}(T \to ht) = 1$$

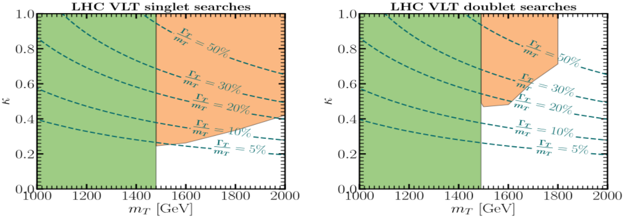
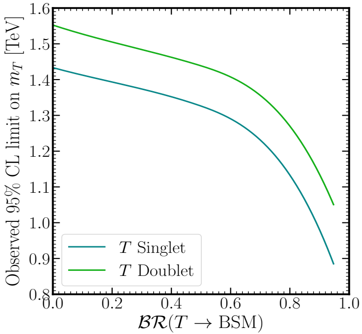


Figure: LHC 95% exclusion on VLT in (m_T, κ) plane: green for pair production, orange for single production limits. R. Benbrik, M. Boukidi, M. Ech-chaouy, S. Moretti, K. Salime, Qi-Shu Yan, JHEP 03 (2025) 020.

Recasted VLT Bounds

If VLT decays to BSM final states, we get a new constraint:

$$\mathcal{BR}(T \to Wb) + \mathcal{BR}(T \to Zt) + \mathcal{BR}(T \to ht) + \mathcal{BR}(T \to \mathrm{BSM}) = 1$$



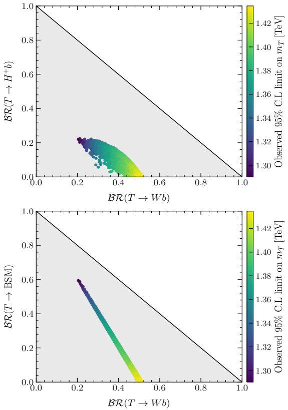
In 2HDM+VLT:

$$\mathcal{BR}(T \to \mathrm{BSM}) = \mathcal{BR}(T \to H^+ b) + \mathcal{BR}(T \to Ht) + \mathcal{BR}(T \to At)$$

2HDM-II + T

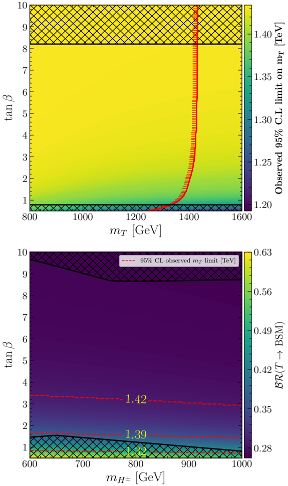
Parameter space scans:

- **2HDM Parameters:**
  - $m_h = 125.1$ GeV
  - m_H: $[130, 800]$ GeV
  - m_A: $[100, 800]$ GeV
  - m_{H^+}: $[600, 1000]$ GeV
  - $s_{\beta-\alpha} = 1$
  - $m_{12}^2 = m_H^2 \cos\beta \sin\beta$ GeV^2
  - $\tan\beta$: $[0.5, 20]$
- **VLT Parameters:**
  - m_T: $[800, 2000]$ GeV
  - **Singlet T:**
    - s_L: $[-0.25, 0.25]$
  - **Doublet TB:**
    - $s_R^{u/d}$: $[-0.25, 0.25]$



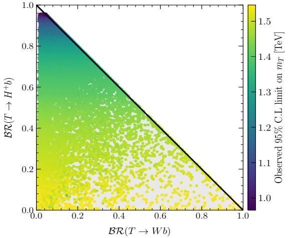
2HDM-II + (T)

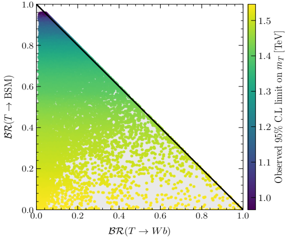
- **Upper panel:**
  - It shows the excluded region (left to the red line) in (m_T, $\tan\beta$) plane.
  - Upper black hatched region is excluded by $H, A \to \tau\tau$ search.
  - Lower black hatched region is excluded by $H^+ \to tb$ search.
- **Lower panel:**
  - It shows the recasted observed m_T limit (red dashed contours) in the ($m_{H^\pm}$, $\tan\beta$) plane.
  - The limit shows slight dependence on $m_{H^\pm}$, and high dependence on $\tan\beta$.



2HDM-II + (TB)

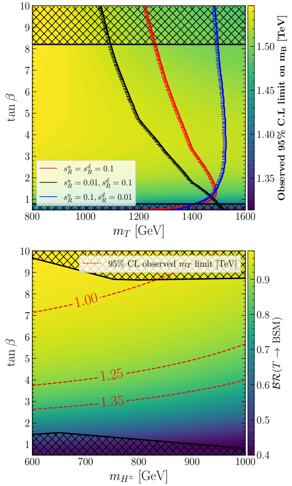
- Observed m_T upper limit scatter in the $(\mathcal{BR}(T \to H^+ b), \mathcal{BR}(T \to Wb))$ plane (left panel) and in $(\mathcal{BR}(T \to \mathrm{BSM}), \mathcal{BR}(T \to Wb))$ plane (right panel).
- $\mathcal{BR}(T \to \mathrm{BSM}) = \mathcal{BR}(T \to H^+ b) \approx 96\%$.
- $\mathcal{BR}(T \to \mathrm{BSM})$ is driven mainly by $\mathcal{BR}(T \to H^+ b)$.
- m_T^{obs} can reach ~ 0.98 TeV.





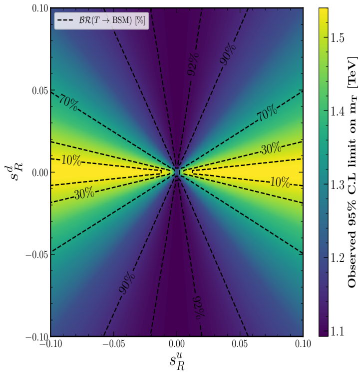
2HDM-II + (TB)

- **Upper panel:**
  - It shows the excluded region (left to the colored line) in $(m_T, \tan\beta)$ plane.
  - For three mixing configurations $s_R^u = s_R^d = 0.1$ (red line), $s_R^u = 0.01, s_R^d = 0.1$ (black line), and $s_R^u = 0.1, s_R^d = 0.01$ (blue).
  - At high $\tan\beta$, when $s_R^d > s_R^u$ leads to significant relaxation of m_T^{obs}.
- **Lower panel:**
  - In the lower panel, m_T^{obs} (red contours) relaxes as $\tan\beta$ is getting high values.
  - With slight dependence on $m_{H^\pm}$ at low $\tan\beta$ and high at its getting larger.



2HDM-II + (TB)

- The Figure shows m_T^{obs} in the (s_R^u, s_R^d) plane with $\mathcal{BR}(T \to \mathrm{BSM})$ shown as black dashed contour lines with $\tan\beta = 3.5$.
- $s_R^d < s_R^u \Rightarrow Z_L^{H^+} > Z_R^{H^+}$ and $Z_L^{H^+}$ is scaled by $\cot\beta$ thus $\mathcal{BR}(T \to \mathrm{BSM}) \searrow$ when $\tan\beta > 1$.
- $s_R^d > s_R^u \Rightarrow Z_R^{H^+} > Z_L^{H^+}$ and $Z_R^{H^+}$ is scaled by $\tan\beta$ thus $\mathcal{BR}(T \to \mathrm{BSM}) \nearrow$ when $\tan\beta > 1$.



Conclusion

- **2HDM-II with singlet T**
  - $\mathcal{BR}(T \to \text{BSM})$ reaches up to 60%, weakening the upper limit from ~ 1.45 to ~ 1.3.
- **2HDM-II with doublet TB**
  - $\mathcal{BR}(T \to \text{BSM})$ reaches up to 100%, weakening the upper limit from ~ 1.55 TeV to ~ 0.98 TeV.
  - Due to $\mathcal{BR}(T \to \text{BSM})$ being driven by $\mathcal{BR}(T \to H^+ b)$.
  - $T \to H^+ b$ can be explored at low mass values.

Thank you